POTENTIAL METHODS FOR IMPROVING PEDESTAL TEMPERATURES AND FUSION PERFORMANCE

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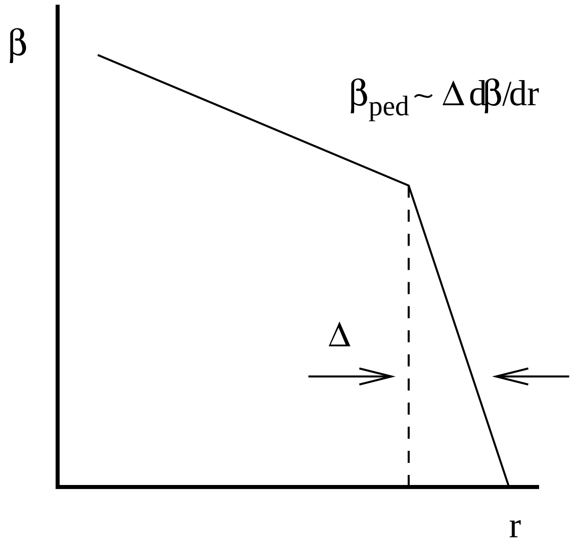
Based on paper presented at 1999 Snowmass workshop,
http://www.ap.columbia.edu/SMproceedings
(also PPPL-3360 (1999))

Edge pedestal scalings very uncertain, but most favor higher-field designs with stronger shaping...

- **Wide range of theory & expt. evidence: $\Delta/R \propto \rho_{*\theta}$ (JT-60U, JET), $\rho_{*\theta}^{2/3-1/2}$, $\beta_{pol}^{1/2}\rho_*^0$ (very interesting DIII-D evidence of a second stable edge, which would have a more favorable scaling to reactors)**



- **Making two assumptions (and use Uckan formula for $q_{95}RI_p/(Ba^2)$):**

  1. **Width $\Delta \propto \sqrt{\epsilon}\rho_\theta \propto \rho q/(\kappa\sqrt{\epsilon})$ (scaling preferred by two largest tokamaks)**
  2. **stability limit $\partial\beta/\partial r \propto [1+\kappa^2(1+10\delta^2)]/Rq^2$ (rough fit to JT-60U, Koide et.al., Phys. Plasmas 4, 1623 (1997), other expts.), get:**

$$T_{ped} = C_0 \left(\frac{n_{Gr}}{n_{ped}}\right)^2 \left[\frac{1+\kappa^2(1+10\delta^2)}{[1+\kappa^2(1+2\delta^2-1.2\delta^3)]}\frac{(1-(a/R)^2)^2}{(1.17-0.65a/R)}\right]^2 \frac{A_i R}{\kappa^2 a}$$

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

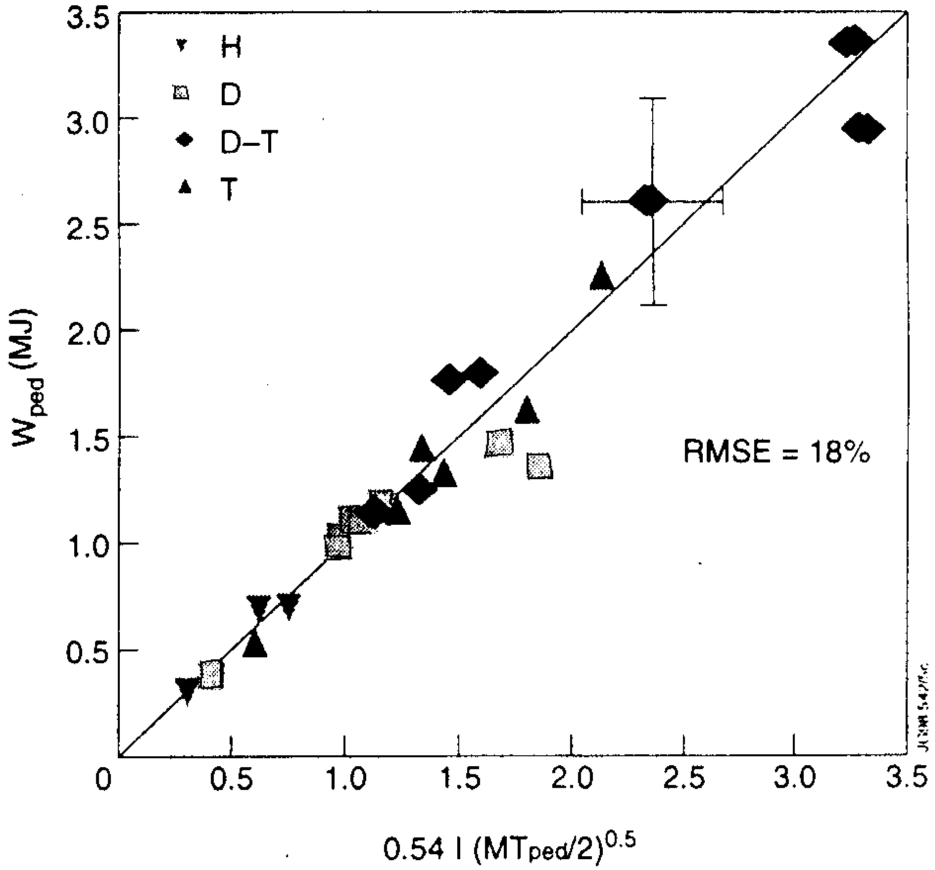


Fig. 4. Scaling of the stored energy in the pedestal (MJ) versus the fit $0.54\ I\ (MT_{ped}/2)^{0.5}$. The symbols are H=Hydrogen, D=Deuterium, D-T=50:50 D-T mixture and T=Tritium.

Cordey + JET Team, IAEA '98

JET data supports $\Delta \propto \rho_{banana}$

+ $\frac{\partial\beta}{\partial r} \propto Rq^2$ model

JT-60U showed the first evidence for the $\Delta \propto \rho_{banana}$, $d\beta/dr \propto 1/(Rq^2)$ model. Also find a strong triangularity dependence.

Kamada & JT60-U
IAEA '96

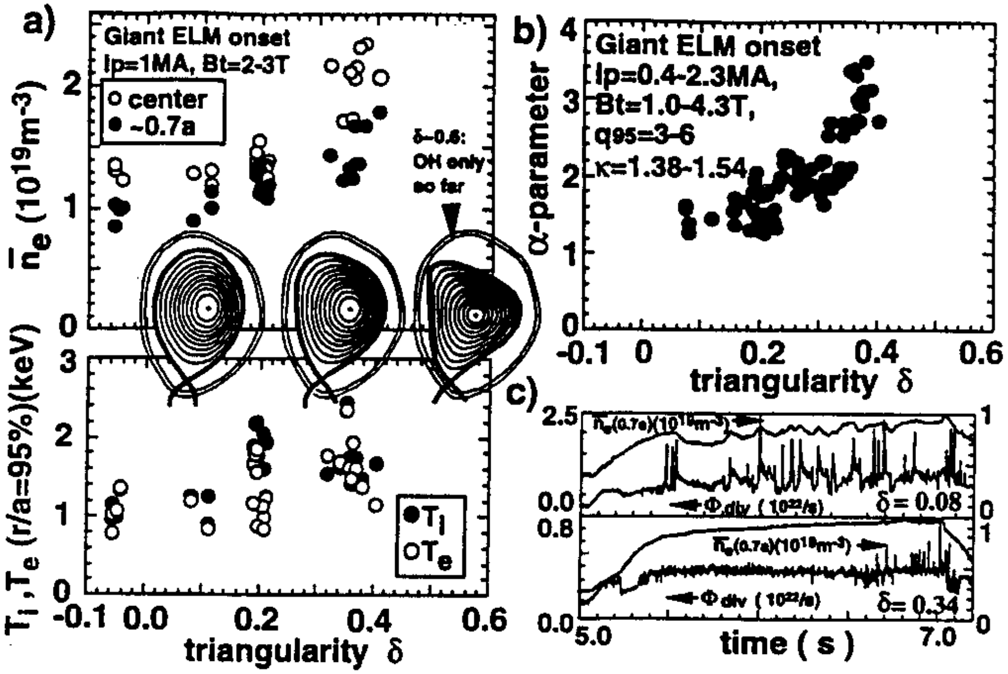


Fig. 1. a) and b): Increasing $\bar{n}_e$ (center chord), $\bar{n}_e(0.7a)$, $T_e(r/a=95\%)$, $T_i(r/a=95\%)$ and edge α-parameter with increasing triangularity at onset of giant ELMs. c): Time traces of D_α^{div} and $\bar{n}_e(0.7a)$ for giant ELMs(δ=0.08) and grassy ELMs (δ=0.34, β_p=2.4) with P_{NB}=20MW and I_p=0.6MA.

Some of the new reactor designs may have significantly improved pedestal temperatures

Using this T_{ped} formula (with a $\Delta \propto \rho_\theta$ assumption), and other pedestal scalings also, to scale from JET to some proposed reactor designs:

	R m	a m	B T	I_p MA	n_{ped} $10^{20}/m^3$	$\frac{n_{ped}}{n_{Gr}}$	$\frac{n_{ped}}{\langle n \rangle}$	κ_{95}	δ_{95}	T_{ped} keV if $\Delta \propto \rho_\theta \sqrt{\epsilon}$	T_{ped} keV if $5\delta^2$	T_{ped} keV if $\Delta \propto \sqrt{Rq\rho}$
JET-norm	2.92	0.91	2.35	2.55	0.4	0.40	~ 1	1.61	.17	2.1	2.1	2.1
ITER-96	8.14	2.80	5.68	21.0	1.3	1.52	1	1.60	.24	0.20*	0.18*	1.5*
lower n_{ped}	8.14	2.80	5.68	21.0	0.6	0.70	.70	1.60	.24	0.94*	0.83*	4.2*
ITER-HAM	6.30	1.81	6.58	13.0	0.86	0.68	.8	1.58	.26	1.4	1.2	4.5
ITER-LAM	6.45	2.33	4.25	17.0	0.64	0.64	.8	1.70	.43	2.0	1.2	5.5
Aries-RS	5.52	1.38	7.98	11.3	1.4	0.74	.67	1.70	.50	3.4	1.9	7.7
FIRE	2.0	0.53	10.0	6.44	3.6	0.48	.80	1.77	.40	4.8	3.0	6.7

* should add $(nT)_{sol}/n_{ped}$ which could be as high as ~ 0.5 keV.

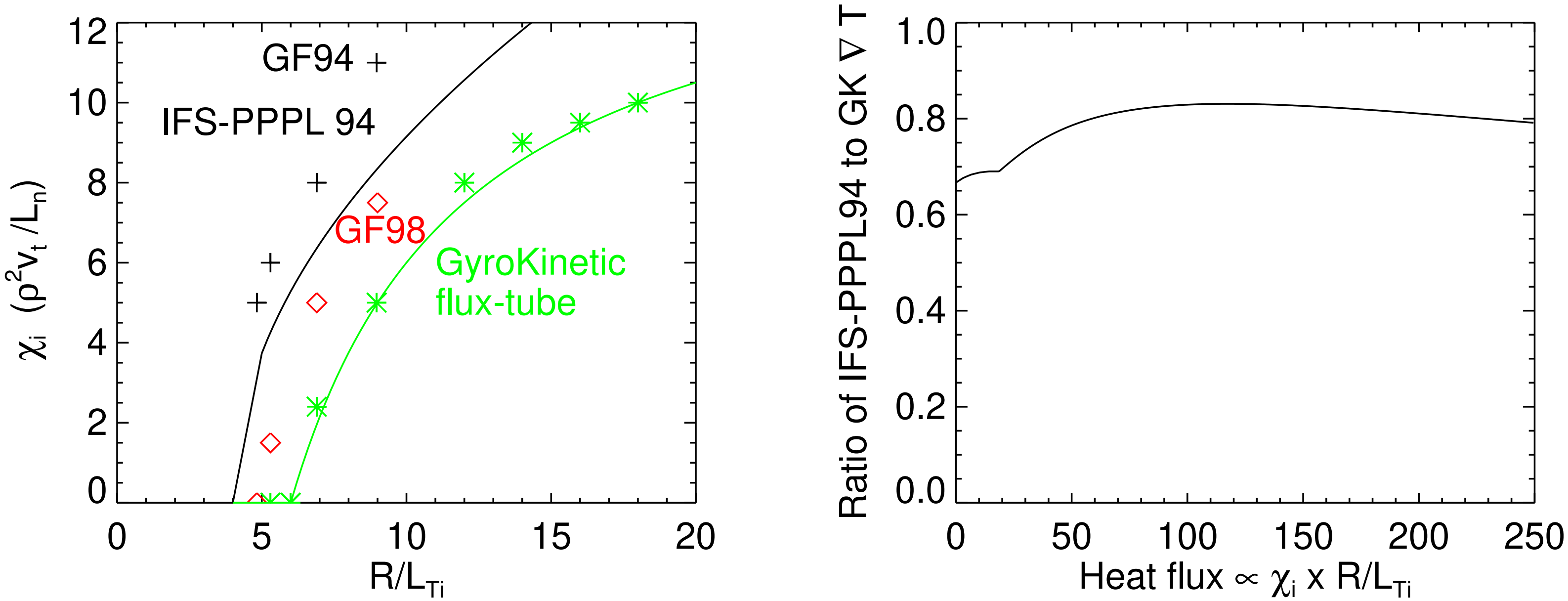
FESAC97: "While, given the present state of knowledge, we cannot provide a reliable estimate for the pedestal parameters in ITER . . ., a pedestal temperature less than 1500 eV, perhaps much less, is a distinct possibility."

Encouraging that even with the pessimistic pedestal scaling ($\Delta \propto \rho_\theta$), it may be possible to get high pedestal temperatures by going to stronger plasma shaping, higher field, smaller size, and modest density peaking.

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

Gyrofluid/gyrokinetic (GF/GK) simulation differences $\longrightarrow$ 20-33% change in predicted temperature gradient

Dimits, Bateman, Beer et.al., PoP 7, 969 (2000)



- **Dimits (LLNL): good convergence in his gyrokinetic particle simulations**

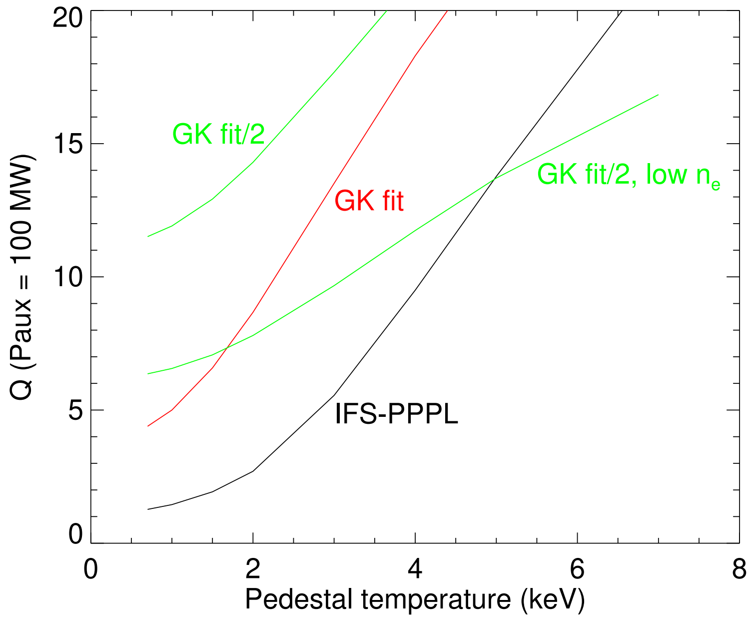
- **New neoclassical gyrofluid closure significantly improves GF/GK comparison.**

- **Turning this plot around, for a fixed amount of heat flux $\propto \chi\nabla T$, the temperature gradient predicted by the original gyrofluid-based IFS-PPPL model is 20-33% low. But $P_{fusion} \propto T^2$, and so may increase by $\times 2$ or more.**

- **Nonlinear upshift in critical gradient may depend on: Rosenbluth-Hinton undamped zonal flows $\uparrow$ with elongation (W. Dorland), $\downarrow$ with weak collisions (Z. Lin), $\downarrow$?? with non-adiabatic electrons [may limit inverse cascade that drives zonal flows (Diamond, Liang, Terry-Horton, Waltz, ...) and $\uparrow$ turbulent viscosity].**

Predictions of Q for ITER-96 from original IFS-PPPL model and from modified version to fit gyrokinetic simulations

Dimits, Bateman, Beer et.al., PoP 7, 969 (2000)



• Gyrokinetic-fit version causes predicted Q to rise some, but the original point remains that the results are sensitive to the assumed edge pedestal temperature, which is uncertain. There is a risk of low Q, particularly at low density.

• The uncertainties are large, and it may be that ITER's pedestal temperature and confinement would be acceptable for ignition. Other sources of uncertainty which need better treatment, in addition to a better understanding of the edge transport barrier and the achievable density and density peaking, include the effects of elongation and plasma shaping, plasma rotation, and fully electromagnetic fluctuations with non-adiabatic electrons.

ITER-96 baseline scenario: $n_e = 1.3 \times 10^{20}/m^3 = 1.5\, n_{\mathrm{Greenwald}}$, $\tau_{He*}/\tau_E = 10$.
lower n_e scenario: $n_e = 1.15\, n_{\mathrm{Greenwald}}$.

CONCLUSIONS, FUTURE WORK

Many caveats, contradictory theories, contradictory experiments:

- **edge very complicated, range of theories, most have width $\Delta \propto \rho^{2/3-1}$.**
- **largest machines (JT-60U, JET) support "standard" model of width $\Delta \propto \rho$ and gradient near the ideal MHD limit**
- **others (DIII-D) support Δ independent of ρ and/or in second stability. Neutrals important in C-MOD?**
- **Useful cross-machine database being developed (Sugihara et.al., EPS99, ITER H-mode Edge Pedestal Expert Group Meeting, March 2000). (Sugihara uses different scaling $dp/dr \propto (1 + 9.26\delta^3.4)$.)**
- **Detailed edge turbulence simulations rapidly becoming more realistic (Xu and Cohen (LLNL), Rogers and Drake (U. Md.), Scott, Jenko, Zeiler et.al. (Garching))**
- **Even with a pessimistic $\Delta \propto \rho$ model, newer reactor designs are able to get significantly improved pedestal temperatures by increasing the field, triangularity, and elongation (which increase the Greenwald density and improve edge stability limits), and by assuming a modest amount of density peaking**